MSNE 510 — Scaling concepts in 2D materials and polymer physics

Contact Information

Instructor: Alberto Pimpinelli Office: SST 301B
Email: ap19@rice.edu
Office Hours: By appointment

Alberto Pimpinelli Spring 2021

Course Objectives and Learning Outcomes

The purpose of this 3-credit graduate course is to provide students with an initial overview of the modern approach to the field of low-dimensional materials. The students will gain what will often be their first exposure to scaling theory and its application to polymers, surfaces, and 2-dimensional crystals through lectures and reading from the research literature.

Students are expected to learn in this course basic and advanced concepts and principles of low-dimensional statistical physics related to phase transitions and critical phenomena, and to apply them to the analysis and explanation of the equilibrium and out-of-equilibrium behavior and properties of engineering materials. Students are in particular expected to learn how to apply scaling concepts to understand thermodynamic properties of polymers and of novel two-dimensional materials.

Suggested Texts and Materials

• Chaikin & Lubensky, Principles of Condensed Matter Physics, Cambridge University Press • Pimpinelli & Villain, Physics of Crystal Growth, Cambridge University Press
• de Gennes, Scaling Concepts in Polymer Physics, Cornell University Press
• Cardy, Scaling and Renormalization in Statistical Physics, Cambridge University Press

Reading from published articles will be assigned. 1

Homework Policy

All assignments should be submitted in hard copies at the beginning of the class one week from the day of assignment or otherwise specified. No late homework will be accepted, please speak with the instructor under special conditions before the deadline.

References

When quoting or giving data from a source other than the textbook, class lecture slides, or one?s own original work, a proper reference must be given. Use ACS format pubs.acs.org/doi/pdf/10.1021/bk-2006-STYG.ch014 or in simpler form at http://library.williams.edu/citing/styles/acs.php

Exams and Papers

There will be a final exam that will consist in a written essai on a reading assigned after the first half of the course. The essai will be returned in the final week.

Grade Policies

HW 40%, Final 60%

Absence Policies

Students are expected to attend all classes. Under special conditions, please seek approval for absence in advance from instructor. Active class participants may receive up to 10% bonus of final grades at the instructor?s discretion.

Rice Honor Code

In this course, all students will be held to the standards of the Rice Honor Code, a code that you pledged to honor when you matriculated at this institution. If you are unfamiliar with the details of this code and how it is administered, you should consult the Honor System Handbook at http://honor.rice.edu/honor-system-handbook/. This handbook outlines the University's expectations for the integrity of your academic work, the procedures for resolving alleged violations of those expectations, and the rights and responsibilities of students and faculty members throughout the process.

Disability Support Services

If you have a documented disability or other condition that may affect academic performance you should: 1) make sure this documentation is on file with Disability Support Services (Allen Center, Room 111 / adarice@rice.edu / x5841) to determine the accommodations you need; and 2) talk with me to discuss your accommodation needs.

Syllabus Change Policy

This syllabus is only a guide for the course and is subject to change with advanced notice.

Course Plan

Reminder of Statistical Physics

- Free energy
- Partition function
- The ideal gas
- The 1D Ising model

Phase Transitions and Critical Phenomena

- Order and symmetry; fluids, liquid crystals and crystals; magnetic order; fractals and random walks; polymers
- Symmetry and order parameters
- First order vs critical behavior
- Correlations: exponentials vs power laws
- Critical exponents
- Upper and lower critical dimensions
- Spin Models and Polymers
  - Ising chain; Potts model
  - Freely jointed chain; polymers as random walks
  - Zimm-Bragg model
  - Application: The helix-coil transition in proteins

Short- vs Long-range Order I

- Short-range order and defects in 1D Ising model
- Long-range order in 2D Ising model
- Lattice walks and the solution of the 2D Ising model

Short- vs Long-range Order II

- Do 2D crystals exist?
- Peierls and Landau's argument; harmonic crystals
- The theorem of Mermin and Wagner; random walks on lattices and long range order
- Power laws and quasi-long-range order; graphene and 2D materials

Phase Transitions in Polymers and Polymer Solutions

- Polymer chains as “critical” systems
- What is a “mean field” approximation
- Flory’s mean field argument
- Self-avoidance and upper critical dimension
- Lattice gas models, polymer mixtures and polymer solutions • Flory-Huggins lattice polymer model
- Osmotic pressure, virial coefficients, and phase transitions
- Coexistence, metastability and the critical point
- Theta point and theta solvents

Spin models and polymers

- Polymers and self-avoiding random walks (SAW)
- De Gennes argument: SAW and “n-components” spin models with n = 0

More on Critical Phenomena

- Mean-field critical exponents: the Bragg-Williams free energy
- Thermodynamic inequalities and critical exponent relations
- Landau’s free energy and the breakdown of mean field

Scaling Theory

- Scale invariance and the correlation length
- Singular free energy and the scaling hypothesis • Exponents and scaling relations
- The Kadanoff construction
- Blocks and decimation procedure
- Renormalizing lengthscales
- The critical point as a fixed point

Introduction to the Renormalization Group

- Order parameter, degrees of freedom, and the reciprocal space
- Summing over degrees of freedom: “momentum shell renormalization”
- Renormalization, rescaling, and iterations;
- Attractive and repulsive fixed points and critical exponents

Renormalization at Work: The Gaussian Model

- Exact renormalization of the Gaussian model (GM)
- Mean field exponents are exact for the GM
- The O(n) models and the "ϕ^4 theory"
- Non-trivial fixed points and non-mean field critical exponents

Topological phase transitions

- The "XY" model in 2D
- High temperature: long wavelength excitations and exponential correlations
- Low temperature: vortices and power laws
- The Kosterlitz-Thouless transition
- Villain's model
- Duality: the Discrete Gaussian and the Solid-On-Solid models
- Renormalization group and the roughening transition of a crystal surface
- Defects and melting of a 2D crystal: graphene